# TELESCOPE MAKING 1

The magazine *for*, *by*, and *about* telescope makers! Fall 1978

## Cassegrain Optical Systems

Introduction

Except for classical Cassegrains, it's virtually impossible to find any written instructions on designing and building compound reflectors. Since almost all professional instruments have conic mirrors, this article provides complete equations — based on third order aberration theory — for calculating Dall-Kirkham and Ritchey-Chretien reflectors that use conic optics. With these equations, you can calculate everything you need to know to build and figure the optics of a high performance telescope.

The source of the equations here is Woodruff and Bettema's article (*Applied Optics*, February 1971, p. 300). The article also gives equations to calculate the aberrations of any compound reflector.

Mathematical Notation

The geometric parameters of a Cassegrain are shown in figure 1. All of these values, with the exception of m and s, pertain directly to the mechanical construction of the telescope. The quantities m and s are needed to prescribe the surface figures of the mirrors. To describe these aspheric surfaces, we used the quantity K. (Note that we depart from Woodruff and Bettema who use a quantity e — not the geometric eccentricity — equal to K + 1. Thus, K = e -1). K is convenient later in calculating the zonal shifts in testing because for a paraboloid K = -1. For a sphere K equals 0, that is it won't show a knife-edge shift at the center of curvature. All the Ks of interest will have negative values, and the knife-edge shift of any concave mirror will be simply K times the parabolic knife-edge shift. Thus, a concave mirror with K = -1.25 will have a shift of 1.25 times that of a paraboloid. An elliptical mirror has its K between 0 and -1. For example, a typical Dall-Kirkham will have a K = -0.7, so its knife-edge shift is only 70 percent that of a paraboloid. With the exception of the Dall-Kirkham, the telescopes we will discuss have hyperboloidal secondary mirrors, that is, K will always be more negative than -1 — typically -3.

Starting a Design

The easiest way to understand these formulas is to actually design a compound reflector. Fig. 1 specifies the parameters that will be used. In beginning the design, you'll need enough clearance behind the mirror to reach the image with enough room left to also use a star diagonal. Generally, no less than the mirror diameter is recommended for this distance.

The size of the secondary mirror is found by the formula:

$$r_2 = (D_1 p / f_p) + (f^0 d / 57.3) \qquad \text{Equation 1}$$

(Note: Equations are numbered consecutively. Those numbers followed by "a" are applications of the equations.)

The first terms are an expression for the axial obstruction ratio which multiplied by the mirror diameter, gives the axial secondary size. The second term gives the added diameter needed for a specified field of full illumination — f degrees, which is the desired field of view measured in radians (divide f degrees by 57.3).

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## A Portable Wooden Yoke Mounting

If you don't have access to a machine shop — but are skilled at carpentry — you can build a wooden mount with simple, easily purchased materials. This mount — intended for a 6 inch f/7 reflector — was made without the use of heavy machinery, yet it has proven to be very sturdy and vibration free.

The first step in building a wooden mount is assembling the tube. Cut four 8 inch squares from 1/2 inch plywood and remove a 7 inch circle from the center of each (see fig. 1). Cut off the corners of the squares to form symmetrical octagons which will be used for baffles in the tube. Then cut four strips of 1/4 inch plywood 48 inches long and the width of the sides of the octagons. Nail and glue them to the opposite sides of the baffles. Space the baffles every 15 inches starting from the front, leaving 3 inches at the rear end for the insertion of the mirror cell. Now plane down the projecting corners of the strips to the level of the adjoining sides, leaving an even surface for placing the remaining strips in place. These strips must be cut wider than the first four because of the increased width of the sides of the octagon (see fig. 1). After gluing and nailing the remaining strips in place, plane down the projecting corners as you did for the first four strips, leaving the outside of the tube in a smooth octagonal shape (see fig. 2).

Because of variations in the dimension of lumber, it's very difficult to give exact measurements for the cradle that holds the tube; therefore, after careful measurement of the tube size, you should build the cradle to fit around the tube. For this 6 inch instrument, a box 8-1/2 inches square (the short

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# TELESCOPE MAKING

The magazine *for, by* and *about* telescope makers!

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# Editorial

The magazine you now hold in your hands is the result, pure and simple, of reader demand. Shortly after we began publishing the "Building A 6" Reflector" series in ASTRONOMY, we noticed a sharp increase in the number of readers asking about building telescopes. Soon, there were more questions than we could begin to answer.

So we began to look for ways to meet the demand and the obvious desire for information. TELESCOPE MAKING is our answer: a magazine devoted entirely to telescope making!

We've tried hard to choose the best possible format for the detailed — and sometimes complex — information that building telescopes requires. At the same time, we've tried to keep the price down by sticking to black and white only, and we've started out with a conservative 16 pages. Those pages filled up so quickly (writing now with 20-20 hindsight) that we almost regret it; so starting with the very next issue, we plan to expand the number of pages — without raising the rates.

We see TM as a magazine that will help people share their ideas and learn from each other. That's why we've called TM "the magazine *by, for* and *about* telescope makers". You — its readers — are also its authors. You, and the telescopes you build, are its subject matter.

A lot of people we've talked to have said "Aha — I see that you're going into competition with *Sky and Tel...* — but that simply isn't true. Telescope makers are a large and diverse group, and for the most part interested in reading everything about telescopes.

Furthermore, it would be foolish for us to ignore the fine job being done by Roger Sinnott in *S&T*'s "Gleanings for ATMs" department, or Dennis di Cicco's invaluable reportage on the ATM meetings. Nor could we bypass a fine magazine edited by Allen Mackintosh: *Telescope Making Techniques*. Published by William Charles Communications. This magazine is also scheduled to appear as a book totaling — each year — some 250 pages! And of course there's the *Maksutov Club Circulars* — another Mackintosh brain child — now being produced by Joseph J. Schmidt, Jr. of the Leheigh Valley Amateur Astronomical Society. We hope that TM will take its place beside these other magazines so that the entire community of "telescope nuts" will benefit.

* * * * *

By the way, we're looking for articles for TM2 and TM3 (Winter '78 and Spring '79). Write to either Bob Cox, 205 E. Elm St., O'Fallon, Mo. 63366 or me at 411 E. Mason in Milwaukee if you'd like to contibute.

Sincerely,

Richard Berry

# An Inexpensive 4" f/10 Reflector

What telescope is best for beginning amateur astronomers — those who just recently became interested in astronomy but, for one reason or another, cannot afford a commercial instrument or want to build their own telescope? The traditional answer has been "the 6 inch f/8, of course; just buy a mirror kit and you're ready to go...."

But experience shows that too few of those 6 inch mirrors ever become part of a functioning telescope. After finishing the mirror there still remains the mounting. In the October 1978 issue of ASTRONOMY, this author proposed that beginners buy a 4 inch f/10 mirror and build only the telescope mounting and tube. Certainly it's not a new idea, but via this strategy, when the work is done the telescope is operational. If it works well, a 6 or 8 inch may then follow.

Plywood and pipe seem to be the ideal construction materials for the mounting, particularly because they reduce the builder's dependence on mail order parts. The inverted fork mount of this design works as well or better than the traditional German equatorial and requires fewer pieces of pipe, reducing the cost. The inverted fork design is also rather forgiving even if it's poorly constructed — a further advantage for a beginner.

The tube is made from plywood in the published design largely because of the author's positive experience with square plywood tubes. Plastic irrigation tubing or cardboard tubing would probably work equally well if the builder finds them readily available.

The weak spot in the design is the pipe

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# Making Pitch Laps

There has always been some sort of mysticism attached to the last phase of telescope mirror making, preparing a pitch lap. But lap making has one simple goal: The action of the lap on the mirror must be reliable and predictable to insure good contact and efficiency in polishing.

Getting the pitch to the correct hardness is the very first step. A tempering agent must be added to the commercial pitch to make it soft enough to accept the polishing agent well. But it must be kept hard enough to sustain its facet pattern in spite of the pressure and heat generated by the polishing process.

Some mirror kits come with a supply of properly tempered pitch. If this is true in your case, you won't have to add anything to it. But if you use commercial pitch in bar form, it will require softening. The agent employed for this purpose is pine tar. Turpentine, beeswax and thinning agents compatible with the chemistry of the pitch are also used sometimes. But pine tar offers good control, doesn't dry out as fast as more volatile agents, and is quite safe to handle. You'll find it at large hardware stores or garden centers, since it's used in tree wound work as well as animal husbandry. It's worth the effort to obtain a can, because it'll last for as long as you'll be making mirrors.

Use approximately 1 ounce of pine tar per bar of pitch. Pour the pine tar into a melting can with a "spout" on one side and drop the broken pitch bars on top. Warm the can, at low heat, on an electric stove or hot plate. Be patient. Use a

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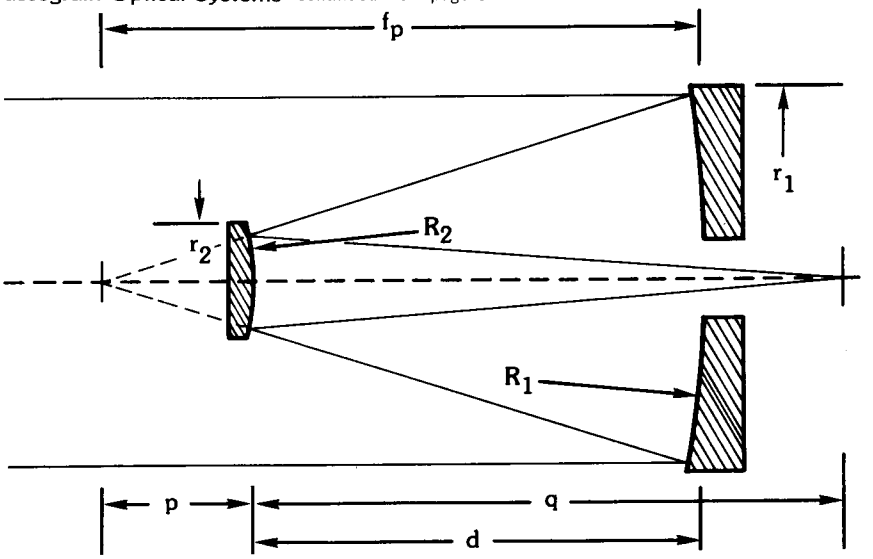
Cassegrain Optical Systems *continued from page 1*




Geometric Parameters of a Cassegrain

$r_1$ = semidiameter of mirror
$f_p$ = focal length of primary (1/2 radius of curvature)
$R_1$ = radius of curvature of primary
$R_2$ = radius of curvature of secondary, considered negative
d = mirror separation
p = prime focus intercept distance (f - d)
q = distance from secondary to Cassegrain focus
m = secondary magnification = q/p (dimensionless ratio)
s = q/d (dimensionless ratio)
e.f.l. = $f_p$xm = effective focal length of the system

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To see how this formula works, let's start with an example where the primary is 10 inches at f/4. The focal length is 40 inches, so $R_1$ equals 80 inches. For a mirror separation of 30 inches, we find p = 40 - 30 = 10 inches. We'll make the distance behind the primary mirror 10 inches following the suggestion above, so q = 30 + 10 or 40 inches. The magnification of the secondary is q/p, or 4, giving a final focal length of 160 inches for the system. For the field of full illumination, we'll use the size of the moon — 0.5 degrees. Thus, using formula 1, we can now find the secondary mirror diameter:

$$r_2 = ((10\times10)/40) + ((0.5\times30)/57.3) = 2.5 + 0.262 = 2.762 \qquad \text{Equation 1a}$$

Most hobbyists can get this far on their own by simply using geometric proportions, but then have difficulty in figuring out the radius of curvature on the secondary. You can find it by using the equation:

$$2/R_2 = 1/p - 1/q \qquad \text{Equation 2}$$

Substituting our parameters into the above equation gives:

$$2/R_2 = 1/10 - 1/40 = 0.075$$

$$1/R_2 = 0.075/2 \; ; \quad R_2 = 26.6666... \qquad \text{Equation 2a}$$

Although it is shown here as a positive number, because of optical sign convention, we'll call it minus later on. You may, of course, round off the numbers, say to 26.667.

It's now necessary to calculate the two quantities needed to prescribe the aspherics, m and s. The formulas for these are:

$$m = q/p \qquad \text{Equation 3}$$

$$s = q/d \qquad \text{Equation 4}$$

By substituting our parameters, we obtain:

$$m = 40/10 = 4 \qquad \text{Equation 3a}$$

$$s = 40/30 = 1.333... \qquad \text{Equation 4a}$$

*continued to page 10*

# Making a 3 Inch Schiefspiegler

People looking through this little Tilted Component Telescope (TCT) have remarked that — for its size — it's the finest performer they have ever used. By following the instructions in this article, you should be able — if you've made at least one mirror before — to build one for your own observing pleasure.

The Schiefspiegler (oblique reflector) is the design of Anton Kutter of West Germany. In sizes of 4-1/4 inches and smaller, it can be built using all spherical optical elements. The 3 inch described here is a scaled-down version of the 4-1/4 inch instrument I first described in *Sky and Telescope* (October 1961), made from plans sent me by Mr. Kutter. Table 1 lists the optical specifications for this 3 inch telescope.

## Making the Optics

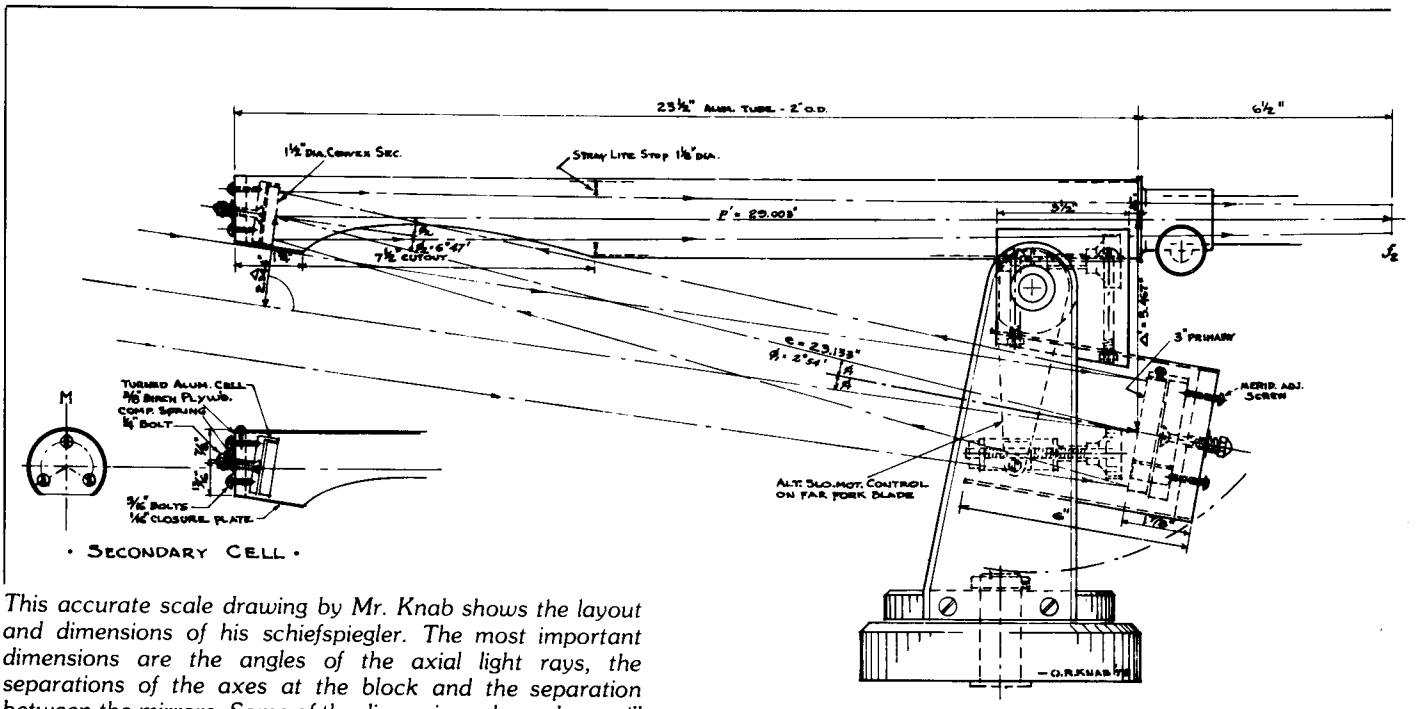
The primary mirror is a 3 inch disk of Pyrex and the tool is a 3 inch disk of 5/16 inch polished plate glass. Since the radii on both mirrors are identical, the center of the tool can be used for the convex secondary mirror. Although plate glass has a higher expansion than Pyrex, using it for the secondary has never introduced any serious thermal problem in observing. If you wish, Pyrex can be substituted, but then the back must be worked flat and partially polished to test through it!

The depth of the final 81 inch radius is only 0.014 inch, about 1/3 that of the standard six inch f/8 reflector, so it's possible to use a smoothing abrasive for roughing out the curve. Grit #220 (66 micron grain size) is adequate for this. An experienced worker, using the proper stroke and pressure, can rough out the curve in 7 or 8 wets.

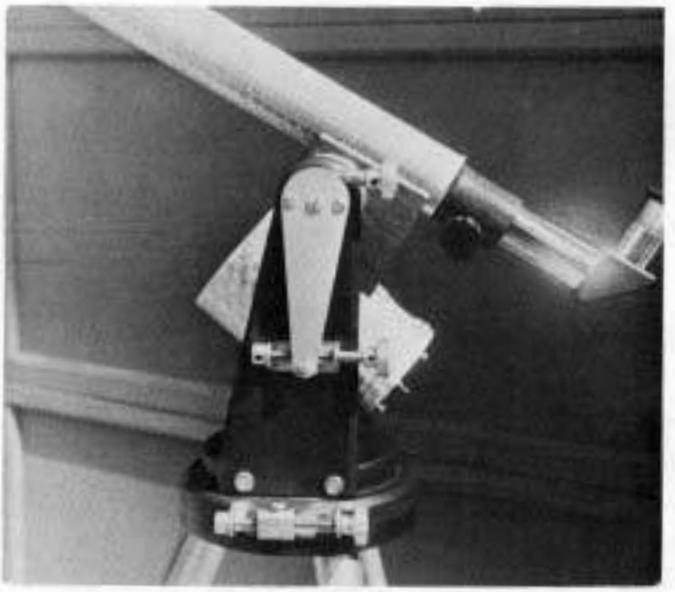
A homemade spherometer with a 1/10,000 inch dial indicator is a must in making these mirrors because the focal length is critical in determining the performance. The mirrors should be held to the design radius to within 1 inch. *Never* allow the radii to become shorter than the design radius (81 inches); if you err, it must be to the long side. If the spherometer used has a radius of 1.4 inch, then the difference in depth readings for a radius of 82 inches — instead of 81 inches — amounts to only 0.00015 inch! The need for a 1/10,000 inch reading dial is obvious. If the radius is more than several inches too long, then you should "breadboard" (mock up) the optics when they're finished and determine the new tilts and spacings.

With the optics rough-ground to curve, the next step is to make the saw cut from the back of the tool to define the secondary. This cut is necessary to relieve strain in the glass tool. Place the tool face down, flat side up, in a wood holder clamped to a drill press bed. Insert a 1-1/2 inch I.D. biscuit cutter in the drill press chuck, carefully centering it on the tool; center as closely as equipment will allow as this will facilitate the final cut when the mirror is finished. A 1-1/2 inch cutter used with the loose abrasive will reduce the size of the final glass disk to an approximate 1.438 inch — a slightly oversize secondary is of no consequence. Make a dam of ordinary putty around the center of the tool to prevent the grit and water from running off the tool during cutting. With water as a lubricant and #120 grit (102 micron) as the abrasive, apply pressure on the cutter 5 seconds, then lift it for 10 seconds. This allows the abrasive to flow back into the cut and prevents the glass from heating up. Wipe out and replenish the abrasive whenever the grinding sound can no longer be heard. Cut down to within 1/16 inch or so of the convex surface, then clean out the cut and fill it flush with drippings from a lighted candle. The tool is now ready to be used to finish the surface for polishing.

Proceeding to #400 (22 micron) abrasive, grind until the #220 pits are removed. 5 to 6 wets will do this. The final abrasive is #2100 (7-1/2 micron) for a total of 7 wets. Continually check the radius and, when necessary, flop the tool

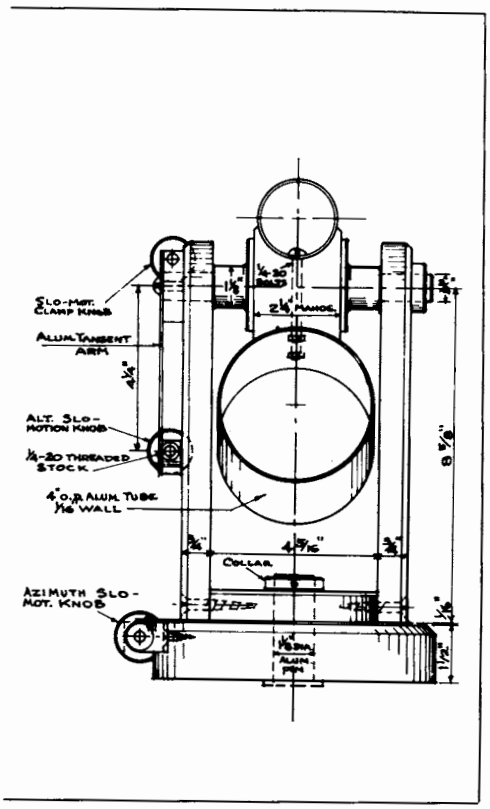



*This accurate scale drawing by Mr. Knab shows the layout and dimensions of his schiefspiegler. The most important dimensions are the angles of the axial light rays, the separations of the axes at the block and the separation between the mirrors. Some of the dimensions shown here will apply only to the instrument built by Mr. Knab because the choice of other materials and slight differences in the mirror radii will cause some variations.*



and mirror to control the radius of curvature so it remains 82 inches (the extra inch allows for shortening of the radius in polishing when the mirror is on top of the lap). At this last stage it will probably be necessary to change the positions of the mirror and tool several times to control the final radius of curvature. Check carefully with a 10x eye-loupe for uniformity of the ground surface. Verify sphericity with the chalk test. When this is achieved, you are ready for polishing.

Put the secondary, or tool, away and use another 3 inch piece of plate glass for the lap base in polishing. (With so shallow a curve on the mirror, it isn't necessary for the base curve to be convex on the tool in order to have a uniform pitch layer.) Pour a lap of standard pitch mixture on the warmed tool to a depth of 3/16 inch to 1/4 inch. When it has cooled sufficiently, cut the channels and work the mirror on the lap to form the polishing surface. "Flash polish" the mirror for 5 minutes using Barnesite or another fast working agent, and then check the surface figure with a Ronchi screen to see if it's a good sphere and if the radius is proper. (This is a check on the accuracy and proper use of your spherometer.) If all is well, continue polishing in 5 minute spells, alternating 5 minutes of pressing, then 5 minutes of polishing. To control the radius, alternate the positions of the mirror and tool, checking with the Ronchi or Foucault test and a tape measure the radius of the curve and the figure. Once you begin polishing, don't use a spherometer. It could result in a damaged surface and is not recommended.




Remember that a long focus sphere is very sensitive to edge turning, so a lap that's too soft is not desirable. Also, the radius of curvature will shorten up much more than an f/8 curve would, hence the necessity to alternate the positions of the two work pieces to control the curve. Before you stop work on the primary, be sure it tests smooth on the Foucault test. Roughness is bad for any optic, but it's *intolerable* in long-focus surfaces.

If the pitch mixture is the right temper, you can make the lap for the secondary by warming it and pressing the convex tool into it. Otherwise, either remake the lap or just add a new thin layer of hot pitch on top of the old lap and then reshape it.

Start polishing the 3 inch secondary disk (former tool) on top of the new (reshaped) lap even though it is convex. It can be flopped over later as required. Remember that we are concerned only with the surface of the blank that will become the secondary mirror. Only this area need pass the test for polish and smoothness of figure; anything outside this area can have pits and a terrible figure. However, in keeping the center smooth and regular, the complete surface will probably have a reasonably smooth finish when the central area is finished.

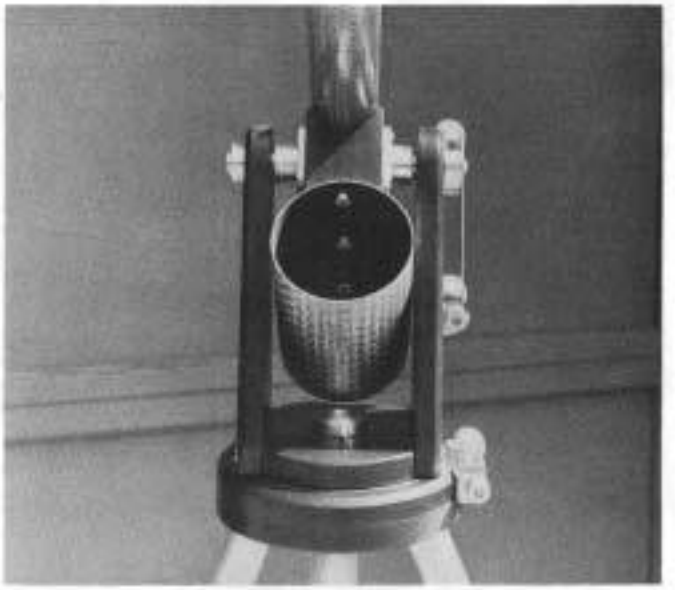
Figure the secondary by using the Ronchi test. Use a 100 line screen and test the convex surface through the flat back of the glass blank. The radius of curvature will be approximately 2/3 that of the design figure (about 54 inches) due to refraction in the plano-convex disk of glass. Reduce chromatic aberration to an acceptable level by using a red filter between the light source and Ronchi screen (red cellophane will do). In the final testing, have no more than two broad Ronchi bands on the test surface. Their edges should be smooth and regular, and the bands should be perfectly straight and parallel.

If you use the Foucault test in this manner, the color effects will be very confusing, even with a red filter. If you made the secondary from Pyrex, the mirror will show irregularities due to the poor internal quality of the glass. Under these conditions, it's difficult to evaluate the figure and smoothness, but by turning the disk and testing across several diameters (notice how the internal irregularities shift), it is possible to determine the mirror's figure.

Actually, the finished surface on the convex mirror will not be spherical due to refraction through the flat surface and the thickness of the glass blank; it will be a weak aspheric curve. However, this effect is so small it can be ignored. The

Table I

| | | |
|---|---|---|
| D | Diameter of Primary Mirror | 3.00 |
| d | Diameter of Secondary Mirror | 1.438 |
| R | Radius of Curvature on Mirrors | 81.0 |
| F | Focal Length of Mirrors | 40.5 |
| p′ | Back Focal Length | 29.0 |
| e | Separation of Mirrors | 23.13 |
| b | Distance Behind Primary of Focus | 5.87 |
| Δ | See Drawing | 2.34 |
| Δ′ | See Drawing | 5.46 |
| $\phi_1$ | Tilt of Primary to Optical Axis | 2°54′ |
| $\phi_2$ | Tilt of Secondary to Optical Axis | 6°47′ |
| F | Effective Focal Length | 71.04 |
| f# | Focal Ratio | 24.5 |



smoothness of the convex surface in this test through the back of the glass is more important than the figure difference!

When the secondary area tests smooth and regular, cut the final disk out of the center of the large one. First tape up the finished mirror surface so it cannot be damaged in handling. Use one layer of high quality masking tape, edge to edge, not overlapped, across the entire 3 inch surface, and then put down another layer at right angles to the first. Place the original biscuit cutter in the drill press chuck. Center the secondary mirror blank, flat side up, in its holder under the cutter. Bring the cutter down until it presses into the wax in the circumference of the cut, then clamp the holder to the drill press base. Raise the cutter, remove and turn over the glass blank, and replace it in the holder. If everything was properly centered originally you can cut down through the mirror surface and join up with the first cut! Make another putty dam right on the masking tape and fill it with a watery solution containing some #1000 grit (15-1/2 micron). Bring the cutter gently down on the taped surface being sure nothing has shifted in the drill press. Continue to use short cutting spells followed with a cooling off period to keep the heat up of the glass low. Too much heat can distort the figure and edge of the final piece of glass! The wax in the cut will prevent the cutout secondary from spinning with the cutter when you break through and finish the cut. As soon as the grinding noise disappears, stop your cutter; you have cut through. Remove the secondary from the glass disk and clean it as follows: Hold the secondary and the 3 inch disk under a fast-running faucet of water, just warm enough to soften the wax and allow the secondary to separate from the rest of the assembly. When all traces of grit are gone, carefully remove the tape and the secondary is finished. It is recommended that you grind a light chamfer on both edges to prevent accidental chipping of the glass in future handling.

When sending the optics for aluminizing, make a strong plywood case with a carefully fitted recess for each mirror, so that under no circumstances can they contact each other or rub against the cover. The cover should be screwed down for easy removal and replacement. Mark it "cover" so it isn't lost.

For a telescope of only three inch aperture, it may be worthwhile to get the enhanced coating (94 percent reflective) in place of the regular aluminizing (88 percent reflective). With two mirrors, 0.94 x 0.94 = 0.8836 of incident light which is reflected to the eyepiece. With the regular aluminizing, 0.88 x 0.88 = 0.7744 which remains. This gain of approximately 11 percent may be worth the extra cost of the enchanced coating.

## Mounting the Optics

While the mirrors are being coated, the work of mounting them can commence. First make a full size drawing on good quality illustration board using the drawing on page 4 for reference. Carefully done, it will enable you to check the dimensions of parts by laying them on the drawing.

Wood is the principle material on the fork and base. For the metal parts, if you lack machine facilities you can (with the ingenious ability of the telescope maker!) find substitute parts in a junk yard or a cellar workshop. Use the plans "as is", or alter them to accommodate the substitute parts.

Mahogany is a good wood, as it's dimensionally stable and easy to work. It was used for the wooden parts of this mounting. The base is made of two 3/4 inch disks glued together with the grains crossed.

The mahogany cradle supporting the two tubes that hold the optics must be carefully made and fitted because the dimension Δ′ = 5.467 inches (see drawing) must be maintained. This distance is determined by the angle between the two optical axes — the one from the primary mirror and the one to the final focus — which is 13°34′. The bottoms of the two tube-mounting surfaces of the cradle should also form this angle with their extended surfaces as bases. To obtain this angle on your full scale drawing, draw a line 16.0625 inches (16-1/16 inches) long, and at the right end point construct a perpendicular line extending down 3.875 inches (3-7/8 inches). Connect the end of this line with the left end of the first line, and you'll have an included angle of 13°34′! To check on the angle of the cradle, place two straight edges along the surfaces of the mounting tube sections and align the top one with the top line of the angle you have drawn. The bottom one should then be coincident with the bottom line. If it isn't, you must correct one of the cradle surfaces until a match is obtained. Since the mounting surfaces for the tubes are below the top of the cradle block, you'll need to move the cradle and straight edges to the left so that the straight edges can be compared with the angle lines.

The cutout in the secondary end of the 2 inch tube can be sawed out with a wire bladed hacksaw and filed smooth. The flat cutoff at the bottom of the 2 inch tube is best cut after fitting the 3/8 inch plywood backing plate into the tube, thereby stiffening the tube end.

The mirror tilt adjusting screws thread themselves into snug holes bored into the 3/8 inch backing plates and push against little recesses in the inner cells.

The primary mirror inner cell is a disk of 3/8 inch birch plywood with 3 little aluminum straps set 120 degrees apart. A TCT should have no obstructions — and this includes edge clips to hold the mirror! In order to preserve the perfectly circular diffraction images, little leather pads were cemented to the edge of the mirror. Three small set screws tapped into the aluminum straps can then hold the mirror by its edges only. The secondary cell is simply a little turned aluminum affair with a ventilating hole in the back surface. It matches the mirror size closely. The secondary has practically no weight, so it is held to the cell with only a strip of masking tape on its ground edge. A thin piece of cardboard with holes to match cell back placed between the mirror and aluminum back will minimize temperature effects between the metal and glass.

The tubes were blackened inside with two coats of blackboard slating. The outside was machine jeweled with steel wool wrapped around a rubber capped wooden dowel in a drill press. While this latter step adds nothing to the performance, it gives a beautiful professional appearance to the assembly. If you have the patience to try it, you'll like it!

The altitude shaft trunnions are made with flanges to receive the mahogany cradle, and are turned for a snug fit inside stock 3/4 inch I.D. oilite bushings, which in turn are a snug fit into the fork ends. The tangent arm slow motion control also acts as a clamp in altitude and locks this axis once an object has been located.

The azimuth axis turns on a 1-1/8 inch aluminum pin with a restraining flange on its lower end. A collar fitting over the upper end holds the base and fork assembly together. No clamp is needed on this axis as the weight of the telecope makes it unnecessary. The slow motion in azimuth is obtained by driving a large flat circular plate that is placed between the fork base and the top of the telescope base. Friction is enough that moving this plate with its tangent arm screw drive carries the telescope in azimuth. If needed to improve friction, glue 6 pieces of 3/4 x 3/4 x 1/16 inch sheet cork to the periphery of the bottom of the fork.

The tripod legs are 1 inch I.D. x 1-5/16 inch O.D. aluminum conduit, available at an electrical supply house. A 10 foot length is enough to make all three legs. The holes in the 1-1/2 inch thick base were done by hand with a sharp wood bit. If they're too loose, shim them with plastic or aluminum sheet for a snug fit.

## Alignment

For rough optical alignment made in daylight, place a dummy eyepiece with a 1/8 inch hole at its back in the holder and tilt the secondary by means of its adjusting screws until the primary cell shows it is concentric in the secondary mirror. (This need never be repeated unless the mirror shifts through rough or excessive handling.) To set the primary, tape a 3 inch cardboard disk just under the secondary tube at its outer end, to indicate the entering bundle of light rays to the primary. Adjust the primary until it looks squarely at this disk, as viewed through the dummy eyepiece; the rough alignment is complete!

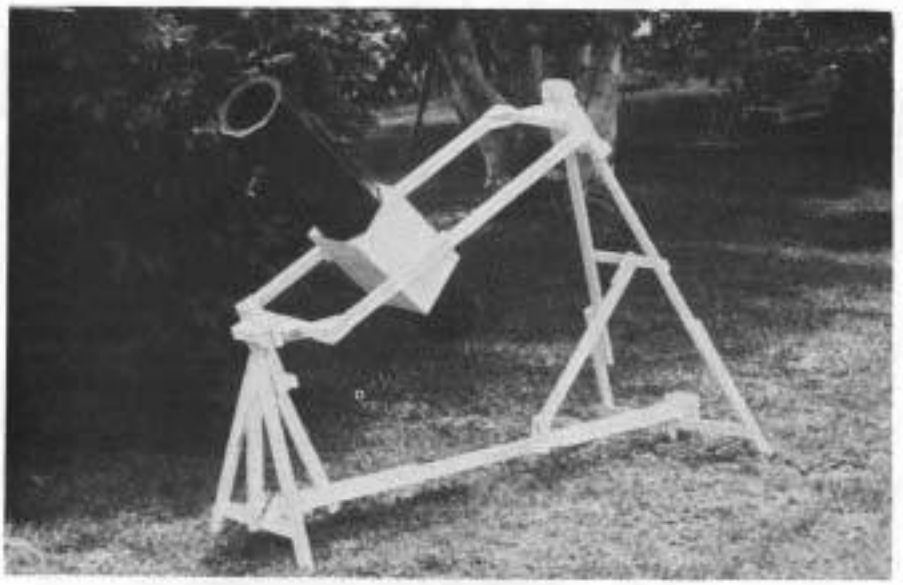
Final alignment is done on a star in good seeing with a medium powered eyepiece. If the out-of-focus star rings are elliptical, adjust the meridional screw of the primary to bring them circular. If they're triangular close to focus, one of the mirrors is pinched too tightly in its cell. Residual coma is invisible, and astigmatism is completely corrected by the tilt angles specified by Mr. Kutter.

The finished intrument weighs only 10-1/2 pounds including the tripod legs and makes an ideal portable telescope for the beginner in tilted component optics.

*Visitors are amazed at the performance of this little telescope! Its images are very contrasty and Saturn looks like it's floating on black velvet. Castor splits easily at around 100 power to show two sharp round Airy disks with a single round, evenly bright spurious ring. On nights of good seeing, the moon stands clear and sharp at 180x with all the detail possible for a 3 inch aperture telescope.*

Oscar R. Knab
Route 3, Box 123
Holiday Island, Ark. 72632

*This picture shows the two tangent arm drives on Mr. Knab's telescope. Both use 1/4-20 threaded rod and traveling nuts to move the instrument. For fast motion in altitude, the clamp is loosened, the telescope shifted and the clamp tightened again. The azimuth has no lock; the weight of the telescope holds it in place by friction. All pictures and drawings in this article by the author.*



*These photographs and drawings show the Sanders' telescope mounting as it actually appears, with dimensions and detailed measurements for their 27°30′ latitude. Note that the parts simply slip together for assembly.*

Yoke Mounting *continued from page 1*

measurement of the outside of the tube) and 16 inches long was made (see fig. 3). Corners reinforced by triangular blocks strengthen the structure and form an octagonal opening into which the tube can be inserted. When the tube has been balanced in the cradle, it can be held in position by the insertion of small wooden wedges.

For larger instruments, the plywood for the cradle should be 1/2 inch thick. To allow for insertion of a larger tube, the cradle can be split as shown in figure 4, with hinges allowing the unit to be readily opened. On the opposite side of the hinges, two clamps — similar to ones used to close trunks — snap shut to grasp the tube tightly in the cradle. On the assembly for a 12 inch tube, it's necessary to use set screws through the side of the cradle to keep the tube from slipping.

In any mounting, the bearings on the polar and declination axes determine the smoothness and stability of the assembly. Threaded bolts turning on a close fitting nut seem to work best. As the accompanying drawings show, the bearings consist of 5/8 x 2-1/2 inch bolts turning on the threads of 5/8 inch nuts. Two bearings are necessary for the polar axis and two for the declination axis.

To make the bearings, locate the center of one side of a 2 x 2 x 8-1/2 inch block of yellow pine and bore a 5/8 inch hole laterally through the block. Then insert a 5/8 inch bolt through the hole until its head rests against the wood (see fig. 5). Draw the outline of the bolt head on the block, remove the bolt, and chisel out the shape of the bolt head to a depth sufficient to recess the head below the surface of the wood. When the bolt is reinserted, the end will extend enough that it will form the bearing surface. All four axles are formed in this same manner, making up the male portion of the bearings.

Mount the declination axis bearing assemblies on opposite sides of the cradle, carefully centering the bolt on the surface. It's now possible to measure the width of the yoke, which will be built of 1 x 2 inch yellow pine (see fig. 6). This instrument required a yoke with outside dimensions of 17 x 58 inches. The corners of the rectangle are reinforced by 4 inch triangles of 1/4 inch plywood placed on both sides of the frame.

The female portions of the declination axis bearings (see fig. 3) should now be constructed, starting with a piece of yellow pine 1 x 2 x 8 inches. Bore a 5/8 inch hole through the center of one side and centering a 5/8 inch nut on the hole, mark the outline with a pencil. Chisel out the form of the nut to the depth of its thickness, and then insert the nut and hold it in place with a 2 x 8 inch piece of 1/4 inch plywood — which has a 5/8 inch hole bored to admit the bolt. Affix a 4 x 8 inch piece of 1/4 inch plywood on each side to form a "U" which will fit over the side bar of the yoke. One of these pieces must be removable in order to place the unit on the yoke. To assemble the bearing, the units are screwed onto the male portions that are fastened to the sides of the cradle. You can slide the bearings up and down the yoke until the balanced tube clears the ends of the yoke. When the proper position is reached, the removable piece of plywood can be tightened down to clamp the assembly in place.

The bolts which form the male portions of the polar axis bearings are now attached to the centers of the ends of the rectangle (see fig. 6) and a measurement made to determine the separation between the upper end and lower polar axis bearing support.

The support for the lower polar axis bearing consists of a vertical "A" frame (see fig. 7) and a 1 x 2 inch member at an angle of 27° 30′ to the vertical (latitude of Bradenton, Fla.). The inclined member receives the unit containing the female portion of the lower polar axis bearing. The "A" frame and the inclined member are integrated with another member which is parallel to the ground and which separates the supports for the upper and lower polar axis bearings. The assembly which contains the female portion of the lower bearing is built of 1 x 2 inch lumber made to slip over and rest on the inclined member of the support. The female portion consists of a 5/8 inch nut embedded in the wood of the unit.

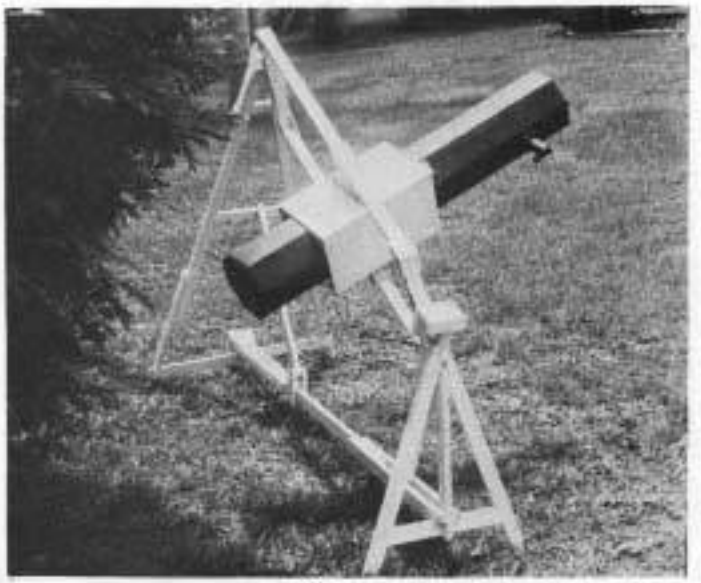
In order to construct the base and bearing assembly properly, the mounting should first be drawn to scale, so you can at least roughly determine the length for the various pieces of wooden structure (see fig. 8). The angle formed by a horizontal line through the lower polar axis bearing, intersects the "A" frame support of the upper bearing at an angle of 62°30′ — and consequently, the angle at the upper bearing is 90 degrees, a right angle. The angle between the horizontal line and lower bearing should equal the latitude of the observer — in this case 27°30′. Using functions of the angles will now enable you to calculate the distances for other members of the structure for the mounting.

Admittedly, lower latitudes are more convenient for this type of mounting, but it should work well for latitudes of 45 degrees or more.

The knock down feature — which in no way interferes with the rigidity of the mount — makes for easy storage and transportation. All the parts fit into the trunk of my car — except for one piece, which can be tied to the top — and the gravity design holds the parts firmly in place.

*My son, Frank C. Sanders, Jr., is a third generation telescope buff. My father and I built our first telescope in 1922 when there was little literature to aid us, and I passed the hobby along to Frank Jr. Today, he combines hobby and business as he teaches physics and astronomy at Southern Illinois University at Carbondale, Ill.*

Frank C. Sanders
206 N. 21st St. East
Bradenton, Fla. 33505



Octagonal Tube

3" 15" 15" 15"

48"

baffle positions

1

¼" plywood

½" plywood baffle

7" diam

End View of Tube

2

8½"

Thin members are 1×2" yellow pine throughout — heavier members would be desireable for a non-transportable mounting

Tube Cradle

16"

side view

3

½" plywood

9½"

8½"

end view

4

¼" plywood

5

1¾"

⅝" nut sunk in wood

1¾"

8½"

Declination Axis bearing — bearing assembly slides in yoke for convenient observing position

5

17½"

6

Unit containing upper bearing slips over this member

¼:1 slope

5

⅝Ø × 2½" bolt with head sunk in wood — 2×2 yellow pine

53"

⅝" nut buried in wood

These drawings for latitude 27°30'

Unit containing lower bearing slips over this member

27°-30'

8

One half is shown

7

AC = BC sin 27°30'
AB = BC cos 27°30'
AD = AC + BE

This member pivots and drops into place to support AD

25¾"

7"

6'9"

2'7"

This member lifts off to separate "A" frame

*continued from page 3*

The aspheric figures are calculated with the following formulas:

| Type | Primary | Secondary | |
|---|---|---|---|
| Dall-Kirkham | $K = \frac{s(m-1)(m+1)^2}{(m+s)\,m^3} - 1$ | $K = 0$ | Equation 5 |
| Classical Cassegrain | $K = -1$ | $K = \frac{-4m}{(m-1)^2} - 1$ | Equation 6 |
| Ritchey-Chretien | $K = \frac{-2s}{m^3} - 1$ | $K = -\frac{-4m(m-1) + 2(m+s)}{(m-1)^3} - 1$ | Equation 7 |

Note the m and s are the same in all of the designs. You may want to compute what the aspherics for each type of design will be in order to see how great a difference there is between them. You can then judge how carefully you need to make the mirrors to get what you want.

For our basic example, the conic expressions for the three types are:

Dall Kirkham

Primary: $K = \frac{1.333(4-1)(4+1)^2}{(4+1.333)4^3} - 1 = 0.2929687$ Equation 5a

Secondary: $K = 0$ (i.e. spherical)

Classical Cassegrain

Primary: $K = -1$ (i.e. paraboloidal)

Secondary: $K = \frac{-4\times4}{(4-1)^2} - 1 = -2.77777...$ Equation 6a

Ritchey Chretien

Primary: $K = \frac{-2\times1.333}{4^3} - 1 = 1.041666...$

Secondary: Equation 7a

$$K = -\frac{4\times10(4-1)+2(4+1.333)}{(4-1)^3} - 1 = -3.1728395$$

The above prescriptions were all ray-traced on a computer as a check on the formulas themselves to see what sort of residual errors due to higher-order aberrations occurred. The computer showed the Dall-Kirkham as good to 1/200 wave, the Ritchey-Chretien to 1/20,000 wave, and the true Cassegrain as perfect.

### Making the Mirrors

The act of figuring a mirror can change its radius. In testing at the center of curvature (radius) of the mirror, the final desired longitudinal reading is found by the formula:

$$z = Ky^2/2R \qquad \text{Equation 8}$$

(This is also the desired longitudinal reading when testing at center of curvature for both source and knife-edge moving together.)

Mathematically, the way to keep the design radius from changing as you figure the mirror is to knock down the edge. However, this is rarely done because of the risk of ruining the figure with a turned-down edge. Since opticians generally deepen the center of the mirror to get the right final radius, start with a spherical radius that is longer by the small amount found from formula 8.

If you remove stock from the middle of the mirror, the depth of stock removal is:

$$s = Ky^4/8R^3 \qquad \text{Equation 9}$$

This is approximately the difference between the spherical and aspheric curves.

The secondary mirror will always be a convex hyperboloid in these telescopes — except for the Dall-Kirkham secondary which is spherical. Professionals figure convex hyperboloids by removing stock mainly at the 70 percent zone. Despite the high K values, the amount of stock removed on a secondary is always much less than on the primary mirror, and the 70 percent zone is the minimum stock removal location. In

**Fig 2 GEOMETRY OF AN ELLIPSE**

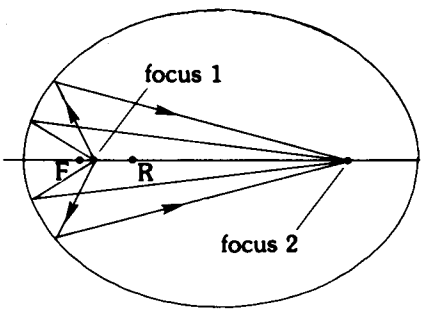



**Fig 3 TESTING AN ELLIPSE AT CONJUGATE FOCI**

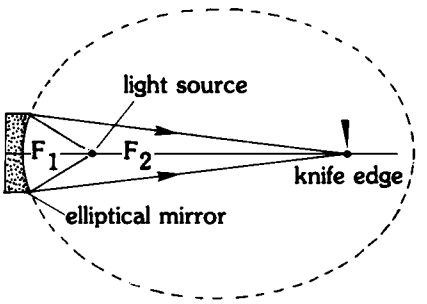



**Fig 4 GEOMETRY OF A HYPERBOLOID**

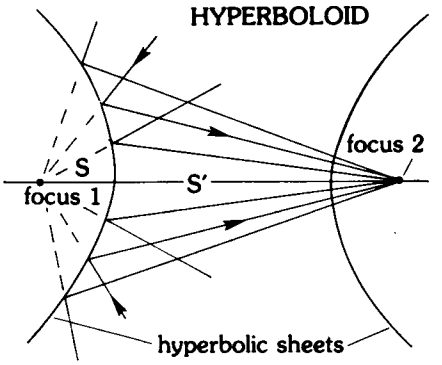



**Fig 5 THE HINDLE TEST**

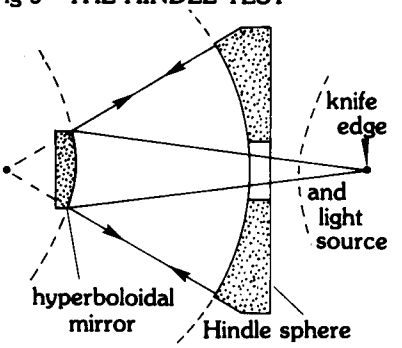
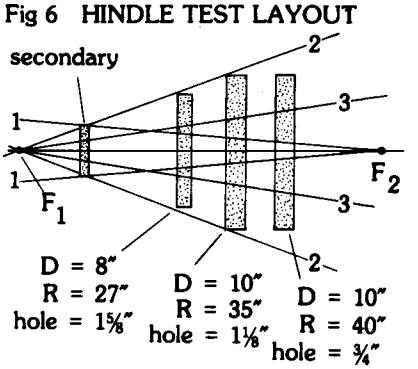



**Fig 6 HINDLE TEST LAYOUT**



order to start with a radius that should end up as the design value, the starting sphere should be long, as given by the formula:

$$R_{start} = R_d/(1+(Ky^4/4R^2_d)) \qquad \text{Equation 10}$$

with $R_d$ the design radius. (Remember that K is negative.) This formula differs from the one for the primary because we're using the minimum stock removal method. Disregarding the above formula sometimes results in a 1/2 percent error in radius on a fast mirror — an amount that is negligible in the average small telescope, but consequential to the large professional telescope.

## Testing Primary Mirrors

The primary mirror's longitudinal knife-edge shift — when the knife-edge and source move together — is calculated by using equation 8. When only the knife-edge is moved, the longitudinal shift is twice as large. Testing may be done as it normally is for parabolic primary mirrors. You should be aware of two other options, however. Professionals use the two lens Offner null test to figure their primaries, but because of the work involved in this test, we recommend using the single lens Dall null test which is simpler to apply.

The elliptical primary of the Dall-Kirkham can be tested to a high precision independent of zonal testing auxiliary optics by testing at its conjugate foci. It's necessary to find the conjugates of the ellipsoid in order to test the figure. The test arrangement is shown in fig. 2 and the formulas for determining the positions of $F_1$ and $F_2$ are as follows: The mirror radius is R, $F_1$ is the short conjugate nearest the mirror surface, and $F_2$ is the distant conjugate. A source at one focus will be perfectly reimaged at the other when you have the correct figure.

We have already found K in the Dall-Kirkham formulas. It is a negative number between 0 and -1 for all Dall-Kirkham primaries. For the mathematician, if the eccentricity of the conic is E, then $K = -E^2$. To find the two foci first calculate the auxillary quantities m, n and o. (M does not mean secondary magnification in these formulae.)

$$m = R/K+1 \qquad \text{Equation 11}$$

$$n = m\sqrt{(K+1)} \qquad \text{Equation 12}$$

$$e = \sqrt{m^2-n^2} \qquad \text{Equation 13}$$

Now calculate the conjugate foci positions using positive values for m and o:

$$F_1 = m-e \qquad \text{Equation 14}$$

$$F_2 = m+e \qquad \text{Equation 15}$$

If you end up with negative values for the two conjugates, check your math for an error.

Let's find the conjugates for the Dall-Kirkham primary mirror of our 10 inch f/4 Cassegrain. For the benefit of the beginner we'll ignore the usual convention of having light travel from left to right, which would make the answers negative, and set up the test as shown in fig. 2 with all distances positive figures.

Let R equal 80 inches and K equal -0.707. The second figure still remains negative because it is not a distance:

$$m = 80/(-0.707 + 1) = 273.038 \qquad \text{Equation 11a}$$

$$n = 273.038 \times \sqrt{-0.707 + 1} = 147.794 \qquad \text{Equation 12a}$$

$$e = \sqrt{(273.038)^2 - (147.794)^2} = 229.579 \qquad \text{Equation 13a}$$

$$F_1 = 273.038 - 229.579 = 43.459 \qquad \text{Equation 14a}$$

$$F_2 = 273.038 + 229.579 = 502.617 \qquad \text{Equation 15a}$$

*continued to page 12*

## Making Pitch Laps

*continued from page 3*

clean stirring rod (metal, not plastic!) or a long stemmed screwdriver to move the bars about. This helps them melt down better and mix with the pine tar.

Don't boil pitch! Not only does it create a smoky, smelly mess, but it isn't necessary.

While the pitch is being prepared for the pouring, you can attend to several other tasks. First you must heat the tool and mirror in water as hot as your hands can stand (140 to 150 degrees Fahrenheit). This is to keep the pitch from cooling and stiffening too quickly when you start to work. Second, you'll need to make a dam around the rim of the tool to retain the pitch after it's poured. Household aluminum foil, folded double from 3 inch wide strips, holds the melt pressure and is high enough to minimize pitch running over the dam — a messy thing at best. Tape several lengths together to go around the circumference of the tool.

Third, prepare your working area. You'll need a surface covered with newspapers, paper towels, a pitch lap mat, nylon netting, and a thick mixture of polishing agent in water. Have everything neat and ready *before* you start. The pitch is the correct temperature when it "flows" when you tip the can. If it runs, it's too hot. Give the hot pitch a good final stirring to get it well mixed — this insures freedom from hard/soft pockets in the final lap — and now you're ready to pour the pitch lap.

Remove the hot tool from its water bath. Dry it with paper towels and set it on a surface covered with plenty of newspapers. Immediately fit the prepared aluminum foil dam strip around the circumference and tape it in place. Pour the pitch; it should flow slowly to the edges if it hasn't been over-heated. There's little danger of breakage if the

A pinhole or slit placed at the near conjugate will be magnified at the distant conjugate 11.57 times. If the positions are reversed, the image of a source at the far conjugate will be reduced 11.57 times at the near one! For telescopes with unusually high secondary magnifications, you'll find that the long conjugate may be so far away as to be impractical for testing. Then it's best to go ahead and knife-edge test the mirror using zonal readings. The longitudinal knife-edge shift is K times that of a paraboloid of the same diameter and radius of curvature — in this case 0.707 times the shift.

Testing Secondary Mirrors

In testing the convex hyperboloids, it's also necessary to locate the conjugate foci of the aspheric. Figure 3 shows the relationship of foci to the secondary mirror. The distances S and S′ are found as follows:

Given the design radius R (a negative number for a Cassegrain secondary) and the value K, the asphericity, which is always a negative number more negative than -1, calculate the auxillary quantities m and n (note that this m is not the secondary magnification):

$$m = R/(K+1) \qquad \text{Equation 16}$$

$$n = -m + \sqrt{m^2 - mR} \qquad \text{Equation 17}$$

Since R is negative, both quantities under the root sign will be positive. The short conjugate is:

$$S = n \qquad \text{Equation 18}$$

and the long conjugate is:

$$S' = 2m + n \qquad \text{Equation 19}$$

Both answers are positive in sign.

As an example, let's calculate the conjugates for a Ritchey-Chretien secondary with R = -26.667 and K = -3.1728395:

$$m = -26.667/(-3.1728395 + 1) = 12.273 \qquad \text{Equations 16a}$$

$$n = -12.273 + \sqrt{12.273^2 - (12.273 \times -26.667)} = 9.588 \qquad 17a$$

$$S = n = 9.588 \qquad 18a$$

$$S' = (2 \times 12.273) + 9.588 = 34.134 \qquad 19a$$

We suggest that you apply formulas 10 to 13 for the true Cassegrain design to determine S and S′ for this system. The answers you obtain will be S = 10 and S′ = 40, the same parameters used in the original design for p and q. This condition exists only for the true Cassegrain, so when laying out a system parameter layout, automatically determine S and S′. Don't take our word for it; calculate S and S′ using the formula to see for yourself.

Now that we've found the positions of the conjugate foci, how is the mirror tested and how are the foci applied? If we place a point source of light at focus $F_2$, then light reflected off the secondary will diverge in a perfect spherical wavefront with its center at focus $F_1$ providing the surface figure of the mirror is an ideal hyperboloid (see fig. 4). A test called the Hindle sphere test uses this situation. A large concave spherical *Hindle mirror* (with a hole in its center to allow light to reach the mirror under test) intercepts the diverging light bundle. The Hindle mirror surface has a radius equal to the distance from $F_1$ to the test mirror surface; therefore, all the light rays are perpendicular to the surface and return upon themselves to return to the $F_2$ conjugate. A knife-edge test shows the perfect hyperboloid as a flat cut-off or null.

Let's lay out a Hindle test for our example for the true Cassegrain. Make the drawing full size or to scale — whichever is convenient (see fig. 6). First draw the optical axis — a horizontal line across the paper — and locate on this line the points $F_1$ and $F_2$ — a distance of 50 inches. Erect a line to the right of $F_1$ perpendicular to the axis at a distance of 10 inches having a length of 2.762 inches (the size we calculated for this secondary) centered around the axis. At $F_2$ measure 10 inches to the left and erect another perpendicular line 5 inches each side of the axis (10 inches long) to represent the Hindle test mirror. Connect the extremes of the secondary with $F_2$ (lines 1) to represent the light from the test source. Also draw lines from $F_1$ through the extremes of the secondary (lines 2) which will represent the expanding light cone from the

*continued from page 11*

tool is pyrex. If it's plate glass, it's doubly important that the pitch not be too hot.

The foil must be removed while the pitch is still plastic and quite warm to the touch. Wait until it loses enough heat to start to solidify, then test by putting your "finger in the pie".

After stripping the foil away in short quick pulls, you'll see where the edge of the lap probably has a turned up curvature — just a bit higher than the inner parts. If, at this stage, you placed the facet forming mat on that flat surface and then put a concave mirror on top of it to make the grooves, you'd find that much of the pitch would run over the edge of the tool. This is a mess!

The key to successful lap formation lies in taking things in hand. Use your hands — covered with some of the polishing agent slurry — to push that elevated edge material towards the center of the lap. Just treat it like it's hot bread dough! The result is an overly bumpy convexed lap shape, still hot and plastic. Now smear some of the polishing agent slurry on the mirror, then press the mirror on this lap — don't use the mat yet — and press down until the curvature of the mirror is carried right out to the edge. Don't waste time at this stage! Immediately after good overall contact is observed, remove the mirror and place the mat (also smeared with the slurry) on

*continued to page 13*

secondary after reflection. Draw lines from $F_1$ through points .625 inches above and below the axis near the center of the secondary (lines 3) to represent the limits of the blind area in the center of this mirror.

In the test — as usually recommended — the Hindle test mirror has the same diameter as the primary, with its radius of curvature equal to the focal length of the original mirror. Examination of our test layout immediately shows that in this instance the test mirror is too small to intercept the complete light bundle from the secondary and must be made larger by about 1-1/4 inches! Few people wish to make an extra test mirror 11-1/4 inches in diameter (besides it's an odd size), so what is the alternative? As the layout shows, you could move the test mirror closer to the secondary, shortening its radius correspondingly. In this example a shift of about 5 inches will permit the 10 inch test mirror to accept the edge rays fromthe secondary.

Unfortunately, the primary cannot be used unless it is reground after the secondary is finished. As the secondary axially obstructs 25 percent of the primary, the blind area at the center of the secondary is 25 percent of its diameter. The two points we marked on its surface near the center represent this loss. Examination of our drawing shows that in either circumstance we won't lose light around the center as there is more than enough room at the mirror center for a hole to permit the light to pass through, yet not restrict the test surface! For the hole size in the Hindle test mirror, measure the size of the light bundle at the mirror surface by using the lines drawn from $F_2$ to the secondary (lines 1) and make the hole equal to the indicated size plus 1/8 inch for safety and convenience.

In drawing the lines from $F_1$ and $F_2$, it's important to keep the lines from F1 through the secondary blind spot points outside the lines from the $F_2$ point to the edges of the secondary, otherwise you'll lose part of the central area of the secondary in the test.

The Hindle mirror may be placed anywhere in the expanding light beam from the secondary, subject to the restriction given above. Keeping standard mirror sizes in mind, if you check the light cone from the secondary you'll see you can place an 8 inch spherical mirror — less expensive and easier to make — at a distance of 27 inches from $F_1$ and still obtain a test of the full surface of the hyperboloid that contributes to the final image.

Applying the principles of fig. 6 can help you chose the smallest size mirror for the Hindle test for any true Cassegrain. The same approach will also determine the Hindle mirror for a test of a Ritchey-Chretien secondary, but the shorter conjugate distances found in our example will result in somewhat different positions for the test mirror. We recommend that you make a layout for our example of the Ritchey-Chretien and note the differences in mirror size versus location.

On very large optics (where a full-size Hindle sphere would be too large), sometimes a smaller spherical test mirror is placed off to one side. The optician can then examine parts of the secondary rather than the whole thing. If you're wondering about errors you might make with the conjugate locations in setting up the test, the accuracy of the short conjugate is more important than that of the long conjugate. As a general rule be sure that both conjugates are measured as precisely as you can when you make your final null determination.

*These equations have been used in the Optical Sciences Center fabrication shop and have been proven time and again on actual optical instruments. So long as your primary is slower than f/2 and your secondary mirror amplification is greater than 2x, the residual on axis higher order aberrations will be entirely negligible. For example, a 10 inch f/4 f/16 Ritchey Chretien calculated using these formulas has a residual spherical aberration of 1/20,000 wavelength of light. (Green mercury light has a wavelength of 0.0000215 inches.) A similar professional instrument — such as the 90 inch f/2.7 f/9 Steward reflector at Kitt Peak Observatory -- using conic mirrors, has a residual of approximately 1/100 wavelength. Your mirrors are likely to lie somewhere between the extremes, and you may place complete reliance on the accompanying formulas.*

*Portions of the above material appeared originally in the Maksutov Club Circular #181, May 1975.*

Dr. Richard A. Buchroeder
Optical Design
Optical Sciences Center
University of Arizona
Tucson, Ariz.

*continued from page 13*

the pitch surface to make your groove pattern. Replace the mirror and exert strong, steady pressure.

In all probability, the pitch will have cooled by now to the point where it will

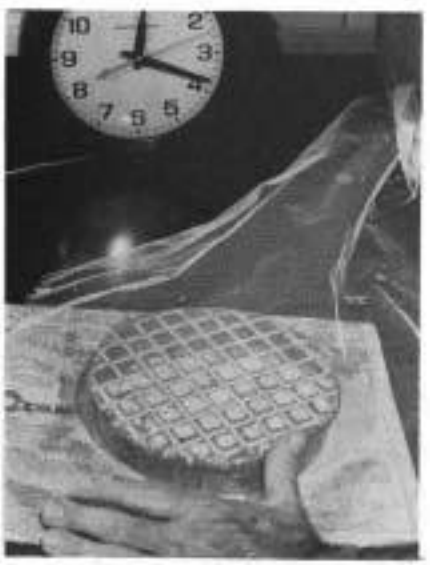
resist indentation. If it does, place both the tool and the mirror into the hot water bath once again. Let the heat soften the

*continued to page 14*

*continued from page 13*

pitch until it becomes workable again. Even if you must do this several times, it still surpasses other ways of making your groove pattern. Once the mat has sunk in as far as it can go (the pitch level will be up to the top of the mat), you're ready for the last step.

The majority of mirrors are made on laps using a large facet pattern. But adding a finer breakdown to the polishing surface — the pattern of dressmaker's nylon — produces a more reliable lap.



Breaking up the face of each facet into many tiny sub-facets, allows the main facet to maintain proper contact with the mirror. But if you try to impress the nylon while the pitch is still thoroughly warmed from the facet forming procedure, you run a risk that the whole facet may start to squash down and fill in the grooves.

The answer to this problem is simple: remove the heat from the entire mass of pitch. Immerse the tool in cool water immediately after the final lap

*continued to page 16*

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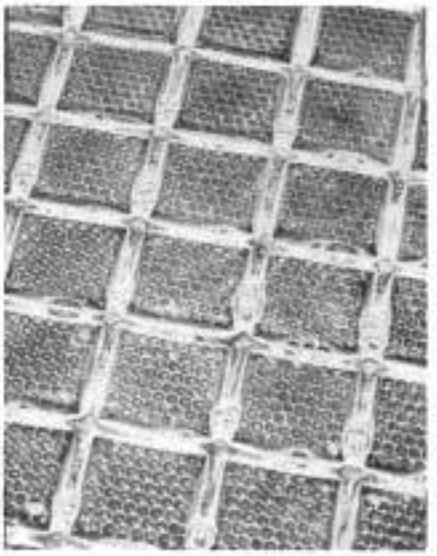
press has been completed. Meanwhile, put the mirror back into a fresh *hot* bath while the tool is cooling. When you're satisfied the pitch has received a thorough cooling, immerse it in hot water for no longer than 15 to 20 seconds. Only the surface of the pitch will soften, making it receptive to the imprint of the nylon mesh netting.

Remove the semi-warm pitch lap and warm mirror from their hot water baths. Quickly place the nylon netting on top of the pitch. Then place the mirror on top of that and press down with a firm steady pressure. If the back of the mirror is clear, you'll see the contact of the pitch being established at the mirror surface. While the pitch surface has some warmth left to it, remove the mirror, strip off the nylon netting and replace the mirror on the pitch surface. With a gentle sliding motion — as used in polishing — bring the mirror and its new lap into perfect contact!

The occasional application of polishing agent to the pitch surface while making the lap not only acts as a release agent (to insure the mirror and tool don't stick to each other), but also imbeds a good working charge of the polishing agent into the mass of the pitch. One more cooling bath and you're ready to begin the polishing routine.

As for future care of the lap, if you have a fairly hard lap, the loss of the nylon mesh pattern will be very slow. You'll not only polish recognizably faster than the old standard lap (that is, one with the nylon net surface), but the lap will also come to proper contact by simply warming the mirror for a few seconds in a hot water bath and going right to work.

*We've used this lap in Macalester College telescope making classes and have found that starting from a polished sphere, we're able to correct a 6 inch diameter standard f-ratio mirror in less*



*than 500 strokes, using the kind of lap described.*

*I recommend this lap making technique because not only does it create a superior polishing surface, but it's probably the easiest of the great variety of lap making methods. Over the years I've tried just about every method and feel qualified in making these recommendations. I'm confident that faithful adherence to my directions will pay dividends in making your next — or present — mirror an easier task.*

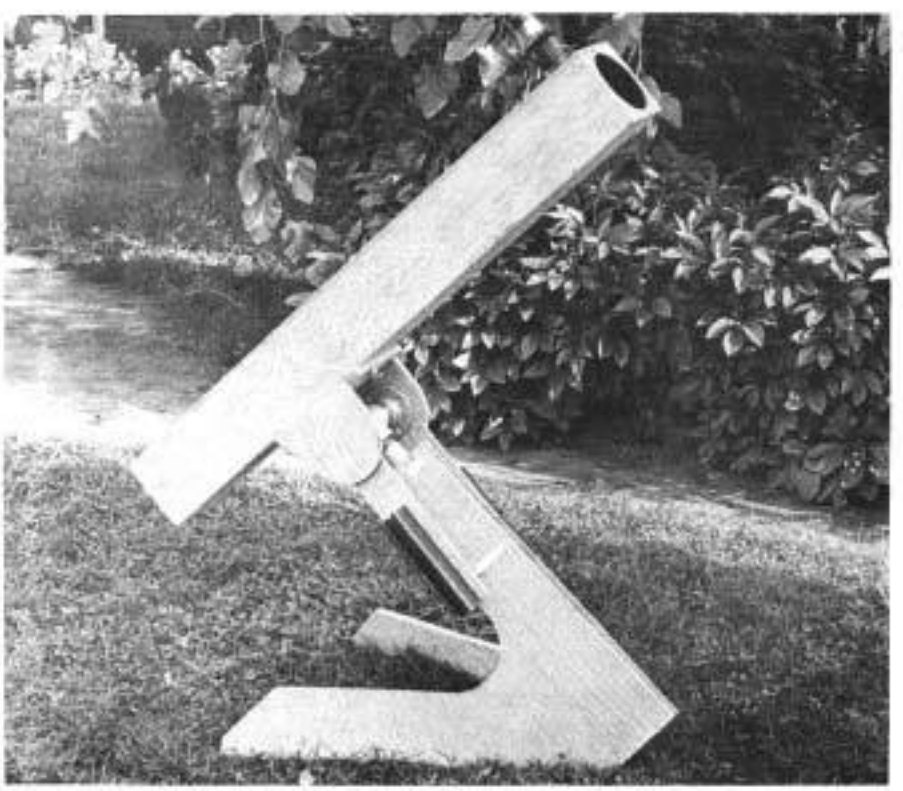
Sherman W. Schultz, Jr.
Macalester College
1600 Grand Ave.
St. Paul, Minn. 55101

## A 4 Inch f/10 Reflector for Beginners

*continued from page 2*

thread bearing that forms the polar axis. Because pipe threads are tapered, in the half-turn from the east point to the west point the bearing goes from too loose to too tight. This can be countered, or at least minimized, by working the pipe threads together with a fine abrasive such as #600 carborundum in a slurry of oil. It's easiest to do this with the 12 inch nipple clamped in a vise, but it can be done reasonably well by swinging the telescope back and forth after the instrument has been completed.

Some ATMs may look askance at the close clearances between the incoming light beam and the walls of the tube. It's traditional to leave an inch or more around the light path in 4 to 6 inch telescopes. However, the prototype telescope has been stored outdoors in an unheated shed and no air currents can be seen in its intra- or extrafocal images of stars; plywood, with its low thermal capacity, apparently is a good wall material.

The mirrors for the prototype were purchased from Jaegers, and they produce excellent diffraction-limited images. It is doubtful that an individual working without direct aid from other ATMs on his first mirror could produce a telescope giving equally fine images. The author's first mirror certainly did not!

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